
# *Abstracts - ICNEM XVII*

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*Updated May 29, 2012*

**Seismic Radiation from Regions Sustaining Brittle Damage**

We discuss a representation theorem for seismic radiation during episodes of brittle instabilities that has, in addition to the standard moment term, a damage-related term stemming from co-seismic changes of elastic moduli [1]. The damage-related radiation is associated with products of the changes of elastic moduli and the total elastic strain components in the source volume. Decreasing elastic moduli in the source region (as produced generally by brittle deformation of low-porosity rocks and explosions) increase the radiation to the bulk, while increasing moduli (which may be produced during the formation of compaction bands in porous rocks) decrease the radiation. Order of magnitude estimates show that the damage-related contribution to the seismic motion, which is neglected in standard calculations, can have appreciable amplitude that may in some cases be comparable to or larger than the moment contribution. A decomposition analysis indicates that the damage-related source term has an isotropic component that can be larger than its double couple component.

The possible existence of isotropic radiation in earthquake source regions is examined [2] using two types of analysis. (i) Derivations of earthquake source tensors with inversion methodology that includes a parameter β giving the percentage of the isotropic component of radiation. Results obtained so far for earthquakes with magnitude $M > 4.5$ in the San Jacinto fault zone (SJFZ) in southern California have source mechanisms with β ranging from 5% to >15%. (ii) Analysis of rotation angles between orientations of standard source tensors constrained to be double couples. Results for aftershocks of the 1992 Landers earthquake and mainshocks in the SJFZ show rotations of early aftershocks that are pronounced near the ends of rupture zones. Synthetic calculations demonstrate that the rotations can be the result of neglecting small isotropic components (as a constraint) in the derivations of the double couple mechanisms.

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**Nonlinear Ultrasound Monitoring of Single Crack Propagation in Cortical Bone**

*Objective* - The origin of bone fracture is still in debate but initiation and propagation of a single critical crack is thought to be one of the main processes leading to bone rupture. Non invasive means for detecting and monitoring the propagation of a single crack is thus highly desirable. We showed in a previous mechanical fatigue experience that nonlinear resonant ultrasound spectroscopy (NRUS) is sensitive to the accumulation of microcracks in cortical bone (Haupert et al. ICNEM 2011, Prague). As a logical extension, the objective of the study was to investigate the sensitivity of NRUS to the controlled propagation in calibrated cortical bone samples of a single crack induced by 4-point bending mechanical loading.

*Materials and Methods* - Twelve human cortical bone specimens were machined as parallelepiped beams (50*2*2mm) to unambiguously identify resonant modes for NRUS measurements. A central notch of 600 μm was made to control crack initiation and propagation during four-point bending loading. The nonlinear hysteretic elastic coefficient ($\alpha f$) was derived from NRUS measurements achieved in dry condition for all undamaged (control state) and damaged (final state) specimens. The experimental setup consists of a piezoceramic emitter bonded with cyanoacrylate at one end of the sample. The longitudinal displacement is measured at the other end by a laser vibrometer. Each bone specimen was probed by a swept-sine around its first compression mode, applying progressively increasing drive levels. Moreover, the buried crack length was assessed by synchrotron radiation micro-computed tomography (SR-μCT) with a spatial resolution of 1.4μm.

*Results, Discussion and Conclusion* - $\alpha f$ increased significantly (up to 60-fold) in the damaged state (44.9±85.4) compared to the initial value (5.5±1.5) in the control undamaged state. Crack length was significantly correlated to the nonlinear elastic parameter $\alpha f$ ($r^2=0.78$, $p<0.001$). Altogether with our previous results from fatigue experiments, these results suggest that NRUS is sensitive to damage accumulation and can be used as a marker of bone damage, specifically to monitor single crack propagation.

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**The Role of Prestress on Propagation and Interaction of Weakly Nonlinear Elastic Waves**

We consider propagation and interaction of weakly nonlinear elastic plane waves in an initially stressed material.

The modeling of a prestressed solid is based on the theory of invariants following the recent work [1]. The strain energy function of an initially stressed material depends not only on the invariants of the strain but also on the invariants of the initial stress.

As was pointed e.g. in [2] stress may induce anisotropy in an initially isotropic medium. We investigate the influence of the prestress on the evolution equations for the amplitudes of weakly nonlinear elastic waves as well as on the waves' interaction coefficients.

*Partially supported by the Polish Ministry of Science and Higher Education Grant no. NN201396937.*

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**The Influence of External Factors on the Elastic Properties of 3-D Unconsolidated Granular Medium**

The nature of propagation of elastic waves in unconsolidated granular media is appreciably different from their propagation in continuous media. State of the contacts between grains has a significant influence on elastic properties of granular media. We present the results of investigations of the influence of external factors (for example, the external variable pressure, the amplitude of the probe signal) on the elastic properties of unconsolidated granular 3-D structure. We used steel balls with a diameter of 2 mm and 4 mm, packed into a cell of the textolite as a model medium. Structure was attached by an external static force, the magnitude of which can be varied. The dependence of the velocity of longitudinal waves on static external compression of the medium was measured. The resulting dependence of the velocity of acoustic waves on the external pressure is proportional to the root of the tenth degree of pressure. The theoretical analysis of the result is presented. The dependence of the velocity of elastic waves on the amplitude of the probe signal for different values of the external static compression was experimentally investigated. The velocity of elastic waves with increasing amplitude decreased. As the external compression increased, the dependence of the velocity of elastic waves on the amplitude of the signal weakened. We present a theoretical analysis of the experimental results.

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**High-Selectivity Imaging of Closed Cracks by Nonlinear Ultrasound**

Crack closure leads to a serious problem of underestimation or overlook in the ultrasonic testing (UT). A novel imaging method, the subharmonic phased array for crack evaluation (SPACE) [Y. Ohara, et al., APL2007, JJAP2009], is effective for solving this problem by measuring closed-crack depths. However, when a short-burst wave is used to achieve a high temporal resolution, not only closed cracks but also linear scatterers appear in the subharmonic array (SA) image owing to leakage in frequency filtering. They are ghosts that degrade the selectivity for closed crack in the SA image.

To enhance the selectivity of closed cracks, we propose two methods. One is the load difference phased array (LDPA) [Y. Ohara, et al, Ultrasonics2011], which uses the subtraction of responses at different external loads. The other one is the amplitude difference phased array (ADPA) [Y. Ohara, et al., JJAP2012 in press], which uses the subtraction of responses at different input amplitudes. The latter has an advantage since there is no need for application of external loads.

We verified the LDPA by a closed fatigue cracks using the servohydraulic testing machine. Furthermore, we propose a practical LDPA with local cooling. By quickly cooling the top surface of the specimen with a cooling spray, only the vicinity of the top surface is thermally contracted, resulting in a thermal tensile stress applied to the closed crack extended from the bottom surface. We verified it by a closed fatigue crack using a linear phased array, monitoring the temperature distribution of the side surface by thermography. Consequently, we successfully observed the crack opening and closing behavior and enhanced the selectivity of closed crack.

We verified the ADPA first by a simulation based on the finite difference time domain (FDTD) method with damped double nodes (DDNs) [K. Yamanaka, et al., APEX2011]. We also verified it by a measurement of a part of a closed crack. The crack was clearly imaged in the subtracted SA images at 4 incident angles, although the selectivity was very low in the original SA images. This allowed us to measure the crack depth.

In conclusion, we succeeded in verifying the LDPA and ADPA. This result will significantly contribute to enhance UT of closed cracks.

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**3D Molecular Dynamics Simulations of Triggering of Slip in Stick-Slipping, Sheared Granular Media by Means of External Vibration: Learned Lessons for Dynamic Earthquake Triggering**

The stick-slip dynamics represents a good description of how earthquakes unfold at mature faults. This dynamic regime is controlled by mechanical and physical properties of the corresponding fault gouge, including its confining pressure and shearing speed. There is increasing evidence that the seismic waves, radiated by an earthquake occurred at an original fault, can trigger earthquakes at other mature faults far away from the original one. This observed phenomenology is termed Dynamic Earthquake Triggering (DET). The DET's underlying physics is still unclear. We use Molecular Dynamics (MD) simulations for modeling mature fault systems taking into account some of their most relevant features for the earthquake physics, including the fault gouge, confined and sheared by extended, deformable blocks mimicking the fault rocks around the fault.

In this presentation, I will report results of 3D MD simulations aiming at investigating the role of the boundary vibration in perturbing the system's spontaneous stick-slip dynamics. I will specifically focus on the role of different perturbation intensities, i.e., what happens when different vibration amplitudes are applied, at various stress levels, during the stick-slip cycle. I will report results in terms of amplitude of triggered slip (if any), measured as macroscopic friction coefficient drop and associated released energy.

The results show evidence of a triggering threshold below which no immediate slip event can be observed. This is in agreement with the observational studies for several dynamically triggered earthquakes (and aftershocks) pointing out that a certain threshold for dynamic strain amplitude is a necessary condition for DET.

The analysis of the respective grain-scale dynamics show no clear evidence of dramatic granular rearrangements in correspondence of the small amplitude external vibration. These observations suggest that tiny and localized contact rearrangements, brought by the applied vibration, are sufficient for the slip onset, unless the amplitude of such perturbations falls below a certain threshold.  Spatial and temporal variations of the released energy, beyond those of other micro- and meso-mechanical variables, are monitored in order to examine the signatures of dynamically triggered and spontaneous slip events.

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**Characterization of Single Contrast Agent Microbubble Vibrations with an Acoustical Camera**

Intravenous injection of lipid-coated gas microbubbles in blood as a contrast agent is performed daily to improve ultrasound imaging of the cardiovascular system. Measuring and understanding the vibrations of contrast agent microbubbles in response to an acoustic wave is essential to optimize the technique employed by an ultrasound scanner to distinguish microbubbles from tissue.

In this context, an acoustical method was developed to retrieve the radial response of single microbubbles to a pressure wave by means of a low-amplitude probing wave. If the frequency of the latter is much higher than the spherical resonance frequency of the microbubble (typically between 1 and 10 MHz), the relative amplitude modulation (induced by a pressure wave) in the signal scattered in response to the probing wave is quasi-equal to the radial strain induced by the pressure wave. A reference probe signal before and after the transmission of the pressure wave allows us to assess asymmetry in microbubble oscillations.

An experimental set-up allows us to insonify single microbubbles simultaneously with two non-collinear focused ultrasound beams to transmit a probing wave at 25 MHz and a pressure wave at 1 MHz. The response of 138 lipid-coated microbubbles to a 1 MHz sine burst with a peak acoustic pressure of 50 kPa was investigated. 8% and 7% showed compression-only and expansion-only behaviors, respectively. The rest exhibited a more symmetrical radial response. A modified Rayleigh-Plesset equation taking into account the additional stiffness and viscosity produced by the lipid coating, as well as the possible buckling and rupturing of the coating, can reproduce the vibrations observed experimentally.

Although efficient nonlinear wave interaction is well known in bubbly liquids, we demonstrate here the possibility to extract quantitative information on bubble vibrations by analyzing the nonlinear coupling between two acoustic waves.

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**General Solutions to the Mechanical Contact Problem**

The origin of acoustic contact nonlinearity is in nonlinear force-displacement relationships for mechanical contacts between surfaces of solids. In this communication, a mechanical model for frictional contact is presented which is applicable for arbitrary shapes of surfaces and for arbitrary loading protocol provided the normal and tangential components are in one plane. The problem has two essential aspects: (i) for complex surface topography, areas of real contact can appear and disappear or merge and split depending on the normal load, and (ii) in the presence of a tangential action, each contact spot consists of stick and slip zones evolving with time; this fact results in a hysteretic and memory-dependent behavior of the solution. The problem of complex topography is solved by using the Jaeger theorem that allows to replace randomly rough surfaces by some equivalent (in terms of force-displacement relationships) axisymmetric profiles of contacting bodies. Then, the solution for an arbitrary loading history is given by the original method of memory diagrams. Its idea is in replacing memory-dependent traction distributions in the contact zone by a simple geometrical object that extracts all memory information from the original traction. The memory diagrams evolve according to a specific algorithm; a given memory diagram allows writing an exact analytical solution for the hysteretic force-displacement relationship. These results are addressed to anyone who is interested in modeling for contact nonlinearity with friction, including complex structures with rough surfaces, cracks, delaminations, cantilevers for surface probing, granular materials, etc.

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**Statistics and Mesoscale Mechanics of 2D Stick-Slipping, Sheared Granular Layers: Improving Our Understanding of Dynamic Earthquake Triggering Physical Controls**

We present a computational modeling investigation of granular stick-slip dynamics and its perturbation by boundary, mechanical vibrations.

The motivation for such study comes from Earthquake Physics and Seismology: in the last 20 years there has been increased evidence that seismic waves, radiated during an earthquake, can interact with other fault systems, far away from the original one, while propagating across them. Sometimes, their passage seems to correlate well with an increase in local seismicity, including actual co-seismic slip events (earthquakes). This observed phenomenology goes under the name of Dynamic Earthquake Triggering and one way for investigating its physical controls consists in performing numerical simulations of stick-slipping fault systems, including fault gouge layers. The stick-slip dynamics mimics the earthquake cycle while the fault gouge seems to play a significant role in making the fault more prone to being perturbed by external factors as seismic vibrations.

We present some results of our work done till now, which consists in Molecular Dynamics simulations of a stick-slipping granular layer (the fault gouge) confined and sheared by deformable elastic blocks (the rocks systems surrounding the actual fault). Mechanical vibrations are introduced into the system in the form of imposed AC displacements of one boundary surface of the system.
The rationale for such simulations is the possibility of investigating both the macroscopic behavior of the system, in terms of stick-slip dynamics and its perturbation by AC vibration and the respective statistical features (slip size and inter-occurrence time statistics, both in the absence and in the presence of applied vibration), and the meso/microscopic one (the granular mechanics that underlies the stick-slip process and its perturbation).

We present here results of both types of investigations, focusing on 2D simulations only, on how the statistics of slip size changes when increasing the intensity of the applied vibration and on the corresponding underlying granular mechanics, analyzed in terms of deformation patterns for the granular layer.

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**FEM Analysis of Anti-Plane Strain Deformation of a Plate with a V-notch of a New Class of Elastic Solids**

The determination of the stresses and strains near a crack tip in a body due to loading has important technological ramifications. In the context of classical linearized elastic theory strain has a 1/sqrt(r) singularity, where r is the distance from the crack tip. As the linearized theory is derived under the assumption of infinitesimal strains, the results are at odds with the basic tenet of the theory. K.R. Rajagopal previously proposed new class of elastic models. These nonlinear models allow finite bounded strains even for infinite stresses and might be well suited to describe the fracturing of brittle elastic bodies. Although these models have nonlinear constitutive relation they fit into framework of small strain elasticity as they use linearized strain tensor. We study a plate with a V-notch being subject to anti-plane strain. Using Finite element method (FEM) we compare model of classical linearized material to the material belonging to the new class of elastic materials proposed by K.R. Rajagopal. The constitutive relation for the classical model is described by one parameter and for the new nonlinear model there are three parameters. We can control strain bound in nonlinear model by these parameters. Using Airy stress function we derive weak formulation of boundary value problem for FEM. We study both models in terms of stress and strain fields around the tip of V-notch for various parameters and angles of V-notch. As the resulting stress fields are for both models similar we focus on comparison of the strain tensor components between classical and nonlinear models.

This presentation is based on joint research with Josef Málek and K.R. Rajagopal.

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**Linear and Nonlinear Resonant Acoustic Spectroscopy of Micro Bubbles Cloud**

In a 4th generation Sodium Fast nuclear Reactor (SFR), the coolant - which is liquid sodium - is topped by an argon cover gas. Due to this presence of argon, various phenomena can lead to gaseous micro bubble presence within sodium. French Nuclear Safety Authority (ASN) requests the associated monitoring, mainly to prevent the formation of large gas pocket and to understand the induced modifications of the sodium acoustic properties.

This study deals with the determination of the void fraction (volumic fraction of free gas) of the bubble cloud. From an acoustical point of view, the water-air couple is a good substitute of the argon-liquid sodium one. For this reason, the first experiments are conducted with an air-water experimental set-up. Micro bubbles clouds are generated with a cavitation-based dissolved air flotation process. A Helmholtz resonator is used as container of the bubble cloud.

First, a linear acoustic method based on the Wood model applied to this set-up is presented. It allows a quantitative link between low frequency speed of sound (frequency lower than bubble's resonance frequency: the so-called Minnaert's frequency) and void fraction. The observed variations of the resonance frequency of the Helmholtz resonator with and without bubble are in accordance with expected void fractions.

Then we applied Nonlinear Resonant Ultrasound Spectroscopy (NRUS) to this set-up. The first objective was to observe the consequences of the nonlinear behavior of the bubble cloud on the Helmholtz resonance. Note that the Helmholtz resonance is far below the bubble's resonant frequency. We present a model of this nonlinear bubbly Helmholtz resonator and associated numerical simulation of NRUS experiments. The second one was to link this nonlinear behavior with bubble's characteristics: void fraction and size. The nonlinear behavior of the cloud is clearly observed but it is difficult to analyze due to the presence of a cavitation phenomenon. This presence makes the second objective nearly impossible to reach… at present time.

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**Cellular Solids: Response to Fluids**

A model of the coupling of an elastic system to a fluid is introduced. One limit of this model is solid-fluid systems that exhibit capillary condensation and associated hysteretic adsorption isotherm, e.g., sandstone. A second limit of this model is a cellular solid, typically elastically soft, e.g., wood. In these solids the hysteretic response comes about because of the fluid-elastic coupling. A sequence of cellular solid models will be introduced and their response to mechanical and chemical potential protocols described.

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**Metastable Elastic Nonlinear Responses of Room-Dry Rocks Revealed by Dynamic Acousto-Elastic Testing (DAET)**

A persistent problem in rocks physics has been the direct relation between material elastic nonlinearity and material microstructure. A physics-based theory with no assumption that directly relates material elastic nonlinearity to damage and other features that may be responsible for the elastic nonlinear response (inter-grain soft bonds, dislocations, microcracks, etc) does not yet exist. New tools are emerging to help characterize the elasticity of materials. We hope that these tools will aid in developing a robust, physics based theory.

A promising new tool is called dynamic acousto-elastic testing (DAET). It relies on exciting a sample with a low frequency (LF) vibration (several kHz) in order to cycle it through stress-strain multiple times. Simultaneously, a high frequency ultrasonic source (1 MHz) applies pulses that probe changes in wave-speed and in attenuation as a function of the low frequency strain. The approach is directly analogous to measuring wave-speed as a function of applied static load, but can be used at modest vibrational strains, can be very applied quickly and can measure changes through tensile and compressive strain. It provides the means to dynamically study the velocity-strain and attenuation-strain relations through the full wave cycle in contrast to most methods that measure average response (e.g. nonlinear resonance ultrasound spectroscopy (NRUS)). DAET has significant implications for the development of a physics-based theory because it provides information that existing methods cannot. Ultimately we hope that the new approach will provide the means to quantitatively relate material nonlinear elastic behavior to the responsible features.

We report the nonlinear elastic response of room-dry rock samples, including a crystalline rock (granite), sandstones and limestones. When increasing the LF strain amplitude from 10^(-7) to 10^(-5), different metastable nonlinear elastic responses are observed, as a result of nonlinear acoustical conditioning. This reversible conditioning modifies nonlinear elastodynamics, each LF strain amplitude brings the material to a different metastable state.

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**Nonlinear Acoustics from Laboratory to Field: Application to Civil Engineering Structure.**

Numerous non-destructive techniques based on nonlinear acoustic have been developed to assess concrete material damage by cracking. These techniques have been demonstrated to be very sensitive compare with linear acoustic techniques. However, if these techniques have shown their relevance in laboratory, their suitability for field utilisation needs to be addressed.
Among the nonlinear acoustics techniques proposed by several researchers for the characterization of micro defects in concrete materials, the ultrasonic travel time shift technique developed at Sherbrooke University, appears to be the most suitable for field work. The technique uses high frequency ultrasonic wave to probe the medium, while a low-frequency high-amplitude wave disturbs the medium, which locally and temporarily modifies its elastic properties. The relevance of this technique was demonstrated in the laboratory and the objective of this work is to study the feasibility of its implementation on site. Two axes have been conducted on this topic. Because the dimensions of civil engineering structures are large and complex shape, there usually is only one workable surface, and the access to the opposite face of the element is not available. In this condition, two configurations are possible for placing the probe transducer. Either both transducers (emitter and receiver) are placed at normal incidence on the same face of the structure or both are oblique incidence transducer on the same face. The objective of this study is to analyze in each configuration, the types of waves generated and also to study the most effective configuration. For the second axis, the idea is to use the traffic as a source of disruptive materials. To do this study in laboratory, a hydraulic jack is used to simulate the passage of vehicles over large concrete slabs made with various reactive aggregates (source of damage due to alkali-aggregate reaction - AAR) and non-reactive aggregates. The results demonstrate the feasibility of in situ implementation of this technique.

Keywords: Nonlinear acoustics, in situ application, ultrasonic time shift technique, civil engineering structure.

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**Review of Neutron+ Experiments to Explore the Physical Mechanisms of Nonlinearity and Slow Dynamics**

Since about 2004, several sets of experiments have been performed to try and understand the physical mechanism(s) of nonlinearity and slow dynamics found in many earth materials. Many of these were classic experiments done simultaneously with neutron scattering measurements, offering a glimpse of what's going on microscopically and meso/macroscopically. A retrospective of what was done and what was learned and what we know will be presented, along with reasons why understanding the causes of nonlinearity might be important.

*Work supported by the Los Alamos LDRD program.*

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## Capturing the Physics of Dynamic Earthquake Triggering in a Friction Law

We develop a physical consitutive law for faulting with the goal of capturing the physics of dynamic earthquake triggering. Current constitutive models used to study seismic faulting, including the laboratory-based Dieterich-Ruina (DR) friction laws, do not capture the most basic observations of dynamic triggering. A transient perturbation applied to a population of faults governed by DR friction causes a decrease in the seismicity rate, while observations show dynamic strains cause an increase in the seismicity rate. We study various potential physical mechanisms and constitutive laws using simple spring slider models, and apply transient stress perturbations to investigate the dynamic response of the constitutive models. We quantitatively examine the resulting rate increase as a function of the perturbation amplitude, which can be tied to seismic observations of triggering.

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**PM Space Density Identification for Nonlinear Physical Systems: "L-2" and "D-divergence" Minimization Methods**

Hysteresis is a phenomenon occurring in ferromagnetic and ferroelectric materials, as well as in a course of deformation of some materials, which are flexible, elastic, or compressible. One of the examples of the non-classical nonlinear materials, for which the hysteresis behavior play the key role, is the sandy rock. In electronics, the hysteresis is produced by positive feedback to avoid an oscillation. Phenomenological models describing hysteresis include PM space based approaches. It became more important during the last years in the field of Nonlinear Elastic Wave Spectroscopy (NEWS), which is in progress with the growing number of NDT technologies. Recently, an active research has been performed for the modeling of nonclassical nonlinear effects in biological tissues using memory based phenomenological approaches [1, 2].

The memristive effects could play a significant role in the complex nonlinear properties of biomaterials, such as tooth [3] or skin [4].

In this contribution, we introduce the hysteresis of electromagnetic relays, which is one of the basic type of hysteresis in electronics. We will present the results of our measurements used for PM Space density identification [5] under the classical ""L-2"" space metric distance or using special statistical nonmetric distances called ""D"" - divergences originated from informationtheoretic concept [6].

Employing these extended ""D"" - divergences we achieve the PM density identification which is more robust against outliers or other measurement errors potentially present in the data sets.

Electronic set-up has been made for studying electronic hysteresis and because of obvious similarity with PM Space Density Identification. Optimized excitations  are studied in the frequency range of 300mHz - 3Hz and in the amplitude range 0 - 50 V . Furthermore, some coded excitations using chirp-like short-time coded signal and modulated excitations were applied in order to test the inversion identification algorithm.

Several hysteresis curves in the "Voltage-Voltage" plane were obtained.

Keywords: Nonlinear nonclassical materials, Electromagnetic relays, PM space, L-2 space, Phidivergences, Density identification, Memristive effects

*This work was supported by the grants SGS12/197/OHK4/3T/14, MSMT INGO-II LG12020, and by the research program of the Ministry of Education of Czech Republic under the contract MSM 210000018.*

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## (Non)Linear (Non)Elastic Deformation of Microporous Materials Subjected to Sorption

Adsorption originates at the molecular scale from the interactions between the atoms of the solid skeleton and the molecules of the fluid. When the size of the pores is in the order of the range of the molecular interactions (micro or nanoporous materials), a mechanical pressure arises orthogonal to the porous interface leading to sorption induced deformations (swelling). Microporous media showing sorption induced deformations are important for a huge variety of engineering application: for instance for sequestration of carbon dioxide in coal, for storage of hydrogen in metal-organic frameworks, for the purification of water etc. They may also be used as moisture activated shape memory materials in e.g. biomedical applications. Sorption in microporous materials may also induce undesired internal effects such as a decrease in permeability or cracking due to a restraining of the deformations. These processes may lead to operational or durability problems.

To study sorption induced deformations in microporous materials, a poromechanical approach is used taking into account explicitly solid-fluid interactions arising in complex random microporous materials. To determine the mechanical effects of adsorption, the amount of adsorbed fluid in the medium has to be known in function of both the chemical potential of the fluid and the volumetric strain of the porous medium. This information can be gained by experiments and by modeling. We are in the first step in exploring the possibilities of a dependent domain approach to link different scales in hierarchical materials in order to determine the macroscopic material properties including coupling coefficients. In the dependent domain theory, the global material behavior results from the interaction of basic elements situated at different scales and characterized by statistical distributions.

Towards developing a framework for the determination of sorption induced deformations using dependent domain theory and computational upscaling, which allows to determine nonlinear coupling coefficient and the hysteretic coupled behavior, we observe experimentally different microstructures containing microporous materials. In particular, we study hierarchical materials like wood, which can be used to develop our understanding of shape memory effects upon moistening.

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**Pore Pressure Evolution During the 'Seismic Cycle' of Laboratory Experiments**

Many seismological observations have reported aseismic creep preceding the nucleation of earthquakes. However the role that pore fluid pressure plays during creep (pre-seismic slip) and how it influences physical and frictional properties of fault gouge are still debated. Dilation associated with aseismic creep is one factor that controls fault gouge evolution, inducing changes in pore fluid pressure and this modifying the stress state within the fault. Increases in pore pressure associated with compaction can favor the propagation of dynamic rupture, due to decreasing stress within the fault and acting as a weakening mechanism.

In order to investigate the evolution of pore fluid pressure during the pre- and co- seismic stages of earthquake cycle, we performed a suite of experiments on synthetic fault gouge in the stick-slip regime, at different effective normal stresses and velocities. We sheared layers of glass beads of known initial grain size (dia. 105-149 μm) in a double-direct shear configuration within a pressure vessel. Effective normal stress ($\sigma'n = \sigma n - Pp$) was kept constant throughout the experiments at values of 2.5, 5 and 10 MPa. Shear stress ($\tau$) was applied via a constant displacement rate at the layer boundaries, and shearing velocity was varied from 1 to 300 m/s. Variations in pore fluid pressure during shearing were measured, under undrained conditions, via two pressure transducers (accuracy 1kPa) positioned on top of the pressure vessel in order to minimize the water volume in the system. Data show log-linear decrease of frictional drop with increasing velocity. Gouge zone thickness during pre-seismic slip is characterized by an evolution from dilation to compaction with increasing velocity at $\sigma'n = 2.5$ and 5 MPa, and only compaction at $\sigma'n = 10$ MPa.

We observe a decrease of pore fluid pressure is observed during the pre-seismic slip, followed by an abrupt increase during co-seismic slip. We find that pre-seismic pore pressure drop increases with increasing pre-seismic slip, indicating a direct correlation between changes in pore pressure and dilation during the pre-seismic stage. On the other hand, we document that with increasing velocity, pre-seismic slip decreases and gouges layers compact, with a pore pressure drop still observed. We hypothesize a non-uniform distribution of deformation within the gouges layers, characterized by an inner gouge zone where elasto-plastic deformation act at the grain junctions reducing porosity, causing the overall compaction, associated with dilation at the boundaries, creating a preferential path for the fluids and generating decrease in pore pressure.

Future post-experiment SEM and particle size analysis will be performed on gouges layers to investigate the influence of grain contacts evolution on pore fluid pressurization.

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**Nonlinear Wave Modulation Spectroscopy: Quasistatic Solution and Experimental Evidence**

Nonlinear Wave Modulation Spectroscopy (NWMS) is one of NEWS methods proven as very sensitive to the variety of material damage ranging from distributed micro-damage to single cracks. The experimental procedure consists of simultaneous excitation of a specimen by two harmonic signals with frequencies f0 resp. f-1. The driving amplitude of lower frequency A0 is usually increased in steps while the amplitude of higher frequency A1 is held constant. Then the parameters of nonlinear model can be estimated through analysis of amplitude dependences of harmonic and intermodulation components. The classical evaluation of the experiment uses a constitutive relation including a classical nonlinear part and a hysteretic (nonclassical) part.

This model predicts dependencies of harmonic and intermodulation components and how they change with presence or absence of hysteresis. Namely in a case of third harmonic amplitude, classical theory predicts proportionality to A0^3, and on the other hand presence of hysteretic component evokes the proportionality changes to A0^2. Similarly, in the case of second order intermodulation sidebands, classical proportionality A0^2*A1 will change with A0*A1. Those relations are valid for wave propagation in nonlinear media, however for a single 2D defect in otherwise linear media no "nonlinear propagation" takes place and a quasistatic solution should be used.

The same constitutive relation was used for quasistatic analysis. The classical nonlinear part of quasistatic solution can be easily solved analytically; the hysteretic part on the other hand has a complicated form. The present work is therefore focused on purely hysteretic response. The magnitudes of the third harmonic and the second order sidebands were studied in dependence on measurement parameters, i.e. excitation amplitudes and frequencies and on nonlinear hysteretic parameter alpha. The shapes of amplitude dependencies of nonlinear spectral components change significantly with varying measurement parameters. By using the scaling relations, an universal dependence of nonlinear spectral components on amplitude ratio was found. That provides a complete solution to the purely hysteretic quasistatic problem. The analysis explains, why left and right sidebands have different magnitudes and how to use this phenomenon for detection and evaluation of hysteresis. The theoretical analysis was supported by experimental results.

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**Quantitative Linear and Nonlinear Resonant Inspection Techniques for Characterizing Thermal Damage in Concrete**

In the context of license renewal in the field of nuclear energy, maintaining in service and re-qualifying existing concrete structures for the period of long term operations is challenging. The integrity of concrete in the concrete pedestal and biological shield wall in nuclear plants remains unknown. These structures have been subjected to radiation and medium temperature for a long period of time. This paper aims at providing some quantitative information related to the degree of micro-cracking of concrete and cement based materials in the presence of thermal damage. We develop a methodology based on linear resonant ultrasound spectroscopy, numerical simulations and nonlinear resonant ultrasound spectroscopy to provide quantitative values of nonlinearity. We show the high sensitivity of derived nonlinearity to thermal damage and its correlation with the evolution of concrete microstructure.

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**Probing Materials Damage at Various Depths by Use of Time Reversal Elastic Nonlinearity Diagnostic: Application to Concrete**

Time Reversal Elastic Nonlinearity Diagnostic (TREND) is based on the use of time reversal to focus energy at a prescribed location. This focused elastic wave energy is then analyzed for nonlinear frequency content. By varying the frequency content of the focused waveforms, the technique can be used to probe different depths relative to the surface, i.e., the TREND will probe the surface and penetrate to a depth defined by the wavelength of the focused waves. We show the validity of this concept by comparing the results obtained from nonlinear resonant ultrasound spectroscopy and the present results in the presence of homogeneously diffused damage in concrete.

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**Multiwave Imaging of the Earth's Subsurface : A Laboratory Scale Feasibility Study**

A recent development in medical imaging is the use of multi-wave imaging methods. The goal of these methods is to overcome the intrinsic limitations of two waves by taking advantage of the resolution of one wave and the contrast of another. As an example, in elastography an ultrasonic wavefield is perturbed by a low frequency shear wave. In this case, the high-contrast shear wavespeed is imaged with a resolution limited by the ultrasound (sub-millimeter). We propose to study the conditions under which new multi-wave high resolution imaging methods can be applied to geophysical applications. An interesting configuration is subsurface imaging on the km scale where a compressional wavefield can be measured between 2 boreholes. A perturbation of this wavefield by shear waves excited at the surface could create a non-linear interaction. To test these ideas we have done preliminary laboratory scale experiments in rocks (berea sandstones). In these experiments, we excite a low-frequency (tens of kHz) shear wave and measure the change in the time-of-flight of a higher frequency (hundreds of kHz) compressional wave traveling perpendicular to this shear wave. We observe both fast and slow nonlinear dynamics in this configuration. This experimental work is in progress.

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**Potential of the Scaling Subtraction and the Cross-Correlation Methods for Osseointegration Monitoring**

Recently the concept of probing the nonlinear elasticity at an interface prosthesis/bone appeared to be a promising method to monitor the osseointegration or sealing of a prosthesis. However, the most suitable method to achieve this goal is a point of debate. To this purpose, two promising methods termed the Scaling Subtraction Method and the Cross-Correlation Method are compared in this study. It is found that one nonlinear parameter derived from the Cross-Correlation Method is as sensitive as a clinical device based on linear elasticity measurement. Further, this study shows that cross-correlation based methods are more sensitive than ones based on subtraction/addition, such like pulse inversion and derived methods. These last methods being widely used in nondestructive testing and contrast agent studies, some improvements could be expected in these domains with the use of CCM.

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## One Channel Time Reversal

Efficiency of time reversal acoustics may be strongly affected by attenuation when the sample Q-factor is very low. This is particularly true when one-channel time reversal is implemented, i.e. taking advantage of virtual sources corresponding to the coda of the signal. Here it is proposed and experimentally validated a procedure which, before back propagation, amplifies properly the recorded signals, in order to optimise the quality of the focusing (signal-to-noise ratio) and the symmetry of the source reconstruction signal.
A numerical application to the reconstruction of non symmetric sources will also be presented.

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**Influence of Noise on the Threshold for Detection of Elastic Nonlinearity**

Nonlinear effects on the propagation of elastic waves in hysteretic media are of great importance, with applications in imaging and monitoring evolution of damage/phase transitions/biological features. However, excitation amplitudes are an issue in order to improve performances of the techniques. Noise effects in the signals can be stronger than nonlinear effects, thus rendering difficult the nonlinear analysis. Here, we analyze in details the link between the amplitude threshold for detection of nonlinear effects and different kinds of noises which might be present in experiments. We also discuss the efficiency of different approaches. Numerical and experimental data will be analysed.

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## Elastic Linear and Nonlinear Behaviors in Slip Processes

In the earth there exist a spectrum of types of slip that range from stick-slip resulting in earthquakes to very slow slip with little accompanying seismic emission. Quasistatic stress changes or dynamic wave forcing may trigger all of these types of slip. We are interested in identifying the 'remote signatures' of slip in the earth, including triggered slips. An example of a remote signature are seismic waves from an earthquake that are recorded at the earth's surface. Another example is the deformation measured by GPS or strain meters located at or near the earth's surface following an earthquake. The signatures may have specific characteristics—for instance seismicity following the main shock of an earthquake generally follows the well-known Gutenberg-Richter relation of seismic magnitude probability, Log (10) N=a-bM, where N is the number of events having an magnitude >= M, and a and b are constants.

When an earthquake is triggered by quasi-static stress changes or by seismic waves, the earth is perturbed in the volume surrounding the slip. Are there specific signatures associated with an 'untriggered' earthquake, a statically triggered earthquake and a dynamically triggered earthquake? That is one fundamental question we are attempting to resolve at present. It appears that changes in earthquake occurrence time (recurrence) are a one signature that can be used to infer slip and possibly distinguish triggered slip from natural slip. Velocity change and thickness or volume change are also potential signatures of interest.

In our exploration of this topic applying laboratory, simulation and seismic data we find strong nonlinear effects. In particular, the memory of a slip event can be very long—for instance the recovery after the (untriggered) magnitude 6.0 2004 Parkfield earthquake continues today based on recurrence time between aftershocks. Accompanying the evolution is dilation, based on some observational evidence as well as laboratory experiments. The dynamic triggering process itself involves a spectrum of behaviors ranging from Mohr-Coulomb type failure to nonlinear dynamical induced failure, based on simulation, experiment and field observation. Examples will be presented.

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**In-Situ Measurement of Velocity Change Under Induced Strong Ground Motion**

Predicting ground motion from large earthquakes is a key ingredient for safe design of critical facilities. Many approaches exist but the most common are to test samples from boreholes, and to make predictions based on the elastic nonlinear properties of the samples. In this paper we present a field demonstration of a new technique that has been previously demonstrated in laboratory studies (Renaud et al., 2009; 2012). Our experimental concept is to dynamically stress a large volume of soil with a low-frequency strain wavefield using a large vibrator truck (T-Rex), while simultaneously measuring the travel-times of high frequency pulses. Compared to existing methods such as measurement of resonance frequency by Johnson et al. (2009), the approach described here is capable of providing local and complete non-linear behavior including all types of hysteresis

The experimental layout consisted of three 0.3 m diameter cased holes augured to 1-, 2- and 3-m depth. Two vertical component accelerometers were carefully driven into the soil a distance of 1 m and 2 m below the high-frequency source to minimize disturbance of in-situ conditions. Sinusoidal cycles of 30Hz were driven from T-rex with varying load levels ranging from 2000 to 50,000 lbs to simulate varying in-situ strain levels.

Two sets of propagation times were measured corresponding to the low- and high-frequency content of the signal. The low-frequency signals show the local velocity increasing corresponding to increasing T- Rex load (15% over a 10-fold increase of strain). The high-frequency content shows a relative decrease of the local velocity with increasing strain imposed by T-Rex, indicating that material softening takes place with larger strain amplitudes. These results are consistent with previous studies of static and dynamic behavior in glass bead packs (e.g., Johnson and Jia, 2005) and in rock. (Zinszner et al., 1997)) and they show that the method may ultimately work well for site characterization.

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**Modeling Shock Waves in Rock and Damage**

Stress driven fracturing of rock is a difficult phenomena to model. Strength measurements of rocks can predict when a rock will yield or break but cannot reliably predict fracture length, orientation and aperture at large scales.

A number of different fracture models are developed beginning with simple shear and tensile failure models in a finite/discrete element code that simulates high strain rate failure in a Hopkinson Bar test. Reasonable agreement between test fracture data density and pattern in a 3D granite model is achieved. However, there is a large computational cost associated with modeling explicit fracturing.

A continuum mechanisms-based fracture model applicable to a broad class of geomaterials is developed. In preliminary applications, the model is calibrated for shale formations using the available experimental data under uniaxial and triaxial stress experiments. We show that the model captures inelastic stress-strain responses prior to the load peak and it predicts the post-critical macro-fracture processes, which result from the growth and coalescence of micro-cracks. In our approach, the fracture zone is embedded into the elastic matrix and effectively weakens the material's strength along the plane of the dominant fracture.

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**Nonlinear Ultrasonic Testing of Carbon Fibre Reinforced Plastics in the Very High Cycle Fatigue Regime**

Carbon fibre reinforced plastics (CFRP) are applied as a light-weight construction material in the aerospace and automotive industries. In such materials, brittle but stiff carbon fibres are combined with a polymer matrix to obtain a high strength to weight ratio. In their lifespan, in service CFRP components are subjected to variable loads, which can amount to 1011 load cycles in a typical life time of more than 20 years. It is therefore important to examine the fatigue of CFRP materials in the very high cycle regime (more than 109 loading cycles). In a joint project a three point bending ultrasonic fatigue testing system was developed at WKK. A high amplitude sinusoidal vibration is added to a static load. The operating frequency of the system f = 20 kHz is used for sample load case and at the same time as input for online ultrasonic monitoring of the fatigue process (IZFP, LZPQ).

Layered CFRP material with a thickness of 4 mm, produced from woven PAN-fibres with a Polyphenylensulfide (PPS) matrix, was investigated. During the fatigue process the vibrations of CFRP samples were measured with a laser vibrometer and a microphone. The analysis methods fast Fourier, short time Fourier and Hilbert Huang transformations were used to evaluate the linear and non-linear spectral content of the signals. Increase of nonlinearity with increasing amount of fatigue cycles was observed. Offline non-destructive testing methods such as X-ray testing, thermography and ultrasonic testing were used to examine the initial state as well as the different fatigue states of the samples during the loading intervals.

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**Strain and Strain-Rate Dependencies in Nonlinear Elastic Solids Applying Dynamic Acousto-Elasticity Testing**

In comparison with standard nonlinear ultrasonic methods like frequency mixing or resonance based measurements that allow to extract average variations of modulus and attenuation versus strain level, Dynamic Acousto-Elasticity Testing (DAET) allows to get the complete dynamic cycle, highlighting in a detailed manner some possible complex nonlinear behaviors. A new collection of data shows that, depending on materials, modulus and attenuation depend primarily on strain, strain-rate or both. Three very different materials are compared with DAET: aluminum, polymer based material and Berea sandstone. Aluminium is shown to depend only (and slightly) on strain. Moreover, its attenuation is independent of strain and strain-rate. This behavior proves that classical nonlinearity based on Landau's theory is suitable for this material.

On the contrary, a polymer used as mock bone highly depends on strain-rate, and only slightly on strain. Finally, Berea sandstone depends both highly on strain and strain-rate. All these different behaviors have several implications in DAET, notably to retrieve the stress-strain signature from the experimental modulus versus strain variations. One systematic procedure is presented and discussed here, which allows to integrate the modulus-strain curve in order to get the stress-strain signature.

This procedure assumes that the experimental modulus extracted from DAET depends on several nonlinear parameters, some of them depending (i) only on strain, (ii) only on strain-rate and (iii) depending on both strain and strain-rate. Parameters depending only on strain (i) can be related to classical nonlinearity, partially or mainly coming from the atomic intrinsic nonlinearity. Parameters depending on both strain and strain-rate (iii) can be related to the hysteretic nonlinearity, often described with the Preisach-Mayergoyz space, and related to mesoscopic scale nonlinearity --friction and/or clapping between grains. However, parameters depending only on strain-rate (ii) were not expected to be present in rocks, i.e., any other previous method was able to highlight them.

This work is closely related to nonlinear viscoelastic models developed in rheology, since the obtained stress-strain curve can be decomposed in three components: one purely elastic, one purely dissipative and one mixed component depending on both. Finally, all this analysis have to be seen with regard to previous quasi-static measurements made in Berea sandstone (Claytor et al, GRL 2009), which show that the hysteretic behavior disappears when the protocol is performed at a very low strain-rate (static limit). Therefore, more work will be needed to link quasi-static and dynamic observations, i.e. the frequency or strain-rate dependence, in the way to fully understand underlying physical phenomena occurring in rocks.

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**Overview of Nonlinear Dynamics Research at Los Alamos**

Los Alamos is renowned for its scientific development over the past 70 years of nonlinear dynamics. This work crosses a range of disciplines and applications, from multi-phase mixing processes and shock physics at extremely small time and space scales, to the slowly-varying dynamics of climate change processes. We present an overview of current research areas within Los Alamos, focusing upon the Geosciences, and discuss collaborative research opportunities, including post-doctoral and graduate student programs.

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**Improving Time Reversal Focusing Through Deconvolution**

Time reversal is a proven technique for focusing wave energy in time and space. A known side effect of the process is the presence of temporal side lobes and spatial fringes which can be undesirable depending upon the application. A deconvolution, also known as an inverse filter, techniques has been developed to improve temporal compression of the focal signal.

This presentation will explore the use of deconvolution in comparison to standard time reversal and provide insight into the process through visualizations of the wavefields. Attention will also be given to the effect of the deconvolution technique upon nonlinear elasticity applications such as the time reversed nonlinear elasticity diagnostic (TREND).

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**Macro-Crack Characterization in Concrete by Diffuse Ultrasound Under Low Frequency Dynamic Loading**

In civil engineering structures, the first layer of concrete plays a role in terms of water-tightness, and contributes to the protection of metal frames from corrosion by external chemical agents (water, CO2, chlorine …). In concrete, a crack reveals a morphology comprised of an external part with a surface opening, and a completely or partially closed part below the surface with potentially partially opened zone.

Conventional ultrasound methods defined by ASTM or ISO normalization are founded on low frequency waves time of flight measurement. Consequently, they are unable to detect a few centimeter scale surface breaking crack. At higher frequencies, strong multiple scattering phenomena occur due to the presence of aggregates, making impossible standard waveform analysis.

The main issue of this paper is to use higher frequencies and to take advantage of multiple scattering by the study diffuse waves transport and its interaction with partial contacts along the crack. The ability of diffuse ultrasound to characterize the opened zone of the crack is shown. However, the closed part of the crack remains imperceptible. To overcome this difficulty, a low frequency dynamic loading is superimposed to diffuse waves in order to alternatively open and close portions the crack. Experimental results associated with numerical simulations show the validity of the method and should subsequently provide physical interpretations about the morphology of a real macro-crack in concrete.

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